Chlorophyll biomass in the global oceans: satellite retrieval using inherent optical properties

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In the upper layer of the global ocean, 2082 *in situ* chlorophyll biomass values $\langle \text{Chl} \rangle$ are retrieved by concurrent satellite-derived inherent optical properties (IOP). It is found that (1) the phytoplankton absorption coefficient IOP alone does not provide satisfactory $\langle \text{Chl} \rangle$ retrieval; (2) the chromophoric dissolved organic matter (CDOM) absorption coefficient IOP must also be used to obtain satisfactory retrieval through $\langle \text{Chl} \rangle \propto a_{\text{ph}} + p a_{\text{CDOM}}$ where p is a constant and a_{ph} and a_{CDOM} are, respectively, the phytoplankton and CDOM absorption coefficients; (3) the IOP-based $\langle \text{Chl} \rangle$ retrieval performance is comparable to standard satellite reflectance ratio retrievals (that have CDOM absorption intrinsically embedded within them); (4) inclusion of the total backscattering coefficient IOP does not contribute significantly to $\langle \text{Chl} \rangle$ retrieval; and (5) the new IOP-based algorithm may provide the possibility for future research to establish the actual role of extracellular CDOM from all sources in the intracellular production of chlorophyll biomass. © 2004 Optical Society of America

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1. Introduction

Historically, satellite retrieval of chlorophyll biomass $\langle \text{Chl} \rangle$ utilizes reflectance ratio algorithms.[1,2] These reflectance ratios strongly suggest that chlorophyll biomass is related to oceanic absorption inherent optical properties (IOPs). Also, independent field measurements have shown that reflectance ratios are correlated with the sum of the phytoplankton and chromophoric dissolved organic matter (CDOM) absorption coefficients[3] ($a_{\text{ph}} + a_{\text{CDOM}}$).

More recently, radiative transfer inversions have provided chlorophyll retrievals concurrently with some IOPs.[4–6] However, the relationship of the principal IOPs, a_{ph} and a_{CDOM}, to $\langle \text{Chl} \rangle$ variability is not clearly revealed in these studies.

The purpose of this paper is to suggest that (1) IOP versus $\langle \text{Chl} \rangle$ relationships can be used to retrieve the chlorophyll biomass and (2) there is a more direct bio-optical link between absorption IOPs and chlorophyll biomass.

2. Theory

First, the historical laboratory correlation of the phytoplankton absorption coefficient versus $\langle \text{Chl} \rangle$ is briefly reviewed to establish the usual operative equation $a_{\text{ph}} = A\langle \text{Chl} \rangle^B$ or $\langle \text{Chl} \rangle = (a_{\text{ph}}/A)^{1/B}$. Second, the connection among $\langle \text{Chl} \rangle$, reflectance ratios, and oceanic absorption IOPs (a_{ph} and a_{CDOM}) is reviewed and established by both radiative transfer and corroborative field experimental findings. Third, the operative laboratory equation $\langle \text{Chl} \rangle = (a_{\text{ph}}/A)^{1/B}$ is generalized to include the a_{CDOM} IOP. Finally, the exponential formulation of the IOP-based $\langle \text{Chl} \rangle$ retrieval relationship is established.

A. Laboratory Retrieval of Chlorophyll Biomass

Experimentally it is found by laboratory measurements of a_{ph} and extracted chlorophyll pigment biomass that

$$a_{\text{ph}} \propto \langle \text{Chl} \rangle. \tag{1}$$

Operationally,

$$a_{\text{ph}} \equiv a^* \langle \text{Chl} \rangle, \tag{2}$$

where a^* is the chlorophyll-specific absorption coefficient (that varies widely depending on light history, nutrient availability, and species).

Copious laboratory measurements yield a more robust relationship[7]:

$$a_{\text{ph}} \equiv A\langle \text{Chl} \rangle^B, \tag{3}$$

which essentially reduces to Eq. (2) when $B = 1$. For laboratory retrievals Eq. (3) yields

$$\langle \text{Chl} \rangle = \left(\frac{a_{\text{ph}}}{A} \right)^{\frac{1}{B}}, \tag{4}$$

where A and B also vary widely depending on light history, nutrient availability, and species. Of course

chlorophyll biomass variability induced by the other principal oceanic IOPs (the CDOM absorption coefficient) is not available through this type of laboratory analysis.

B. Oceanic Retrieval of Chlorophyll Biomass

The satellite retrieval of chlorophyll biomass in the real oceanic environment is considerably more complex than laboratory filter pad absorption measurements of a_{ph} and the corresponding chlorophyll biomass extractions. Specifically, it can be shown that $\langle Chl \rangle \sim a$ (the total absorption), and this is the fundamental basis of the algorithm derived here. This is achieved through simple radiative transfer theory and field experiments.

First, for many years it has been shown that chlorophyll biomass is related to water-leaving reflectance ratios[1,2] or

$$\langle Chl \rangle \propto \text{reflectance ratios.} \qquad (5)$$

The reflectance ratio chlorophyll algorithm is essentially a total absorption algorithm. This can be easily shown when we recall that at 443 nm (the approximate absorption peak of chlorophyll pigment) the reflectance R is roughly approximated by $R_{rs}(443)$ = constant $\times$ $b_b(443)/a(443)$; and at the lower chlorophyll absorption hinge point, $R_{rs}(555) =$ constant $\times$ $b_b(555)/a(555)$ where b_b is the total backscattering coefficient and a is again the total absorption coefficient. Thus a reflectance ratio can be formed: $R_{rs}(555)/R_{rs}(443)$ $\sim$ constant $\times$ $b_b(555)/b_b(443)a(443)/a(555)$. It is subsequently found that backscattering has little influence on the $\langle Chl \rangle$ variability, but at this point in the derivation the backscattering ratio $b_b(555)/b_b(443)$ is assumed to have modest variation. Thus $R_{rs}(555)/R_{rs}(443)$ $\sim$ constant $\times$ $a(443)/a(555)$. Then, because IOPs can be rigorously summed,

$$\langle Chl \rangle \sim \text{constant}$$
$$\times \frac{a_{water}(443) + a_{ph}(443) + a_{CDOM}(443)}{a_{water}(555) + a_{ph}(555) + a_{CDOM}(555)}.$$

The reflectance ratio can be expressed entirely in terms of the absorption at a reference wavelength. Using 443 nm as the reference wavelength, we obtain $a_{water}(555)$ = $C_1 a_{water}(443)$ and $a_{ph}(555)$ $\approx$ $C_2 a_{ph}(443)$ (Ref. 8); for a CDOM spectral slope of $\sim 0.017/nm$, $a_{CDOM}(555) \approx 0.15\, a_{CDOM}(443)$, yielding

$$\langle Chl \rangle \sim \text{constant}$$
$$\times \frac{a_{water}(443) + a_{ph}(443) + a(443)_{CDOM}}{C_1 a_{water}(443) + C_2 a_{ph}(443) + 0.15\, a(443)_{CDOM}}.$$

4. Summary and Discussion

On the basis of historical reflectance ratios, recent ship cruise findings,[3] and radiative transfer theory, a new absorption-based chlorophyll biomass algorithm is derived. When used to retrieve 2082 *in situ* global chlorophyll biomass values, the IOP-based algorithm [Eqs. (11) and (12)] is found to be comparable in performance to the standard SeaWiFS OC4v4 chlorophyll biomass algorithm. However, unlike reflectance ratio algorithms, the new IOP-based algorithm allows studies of chlorophyll biomass variability as a function of phytoplankton and CDOM absorption. For example, the chlorophyll surface (Fig. 3) shows significant biomass variability for small amounts of phytoplankton and CDOM absorption.

For chlorophyll biomass variability, the exact role of CDOM absorption is not yet understood but it is hypothesized here to be related to phytoplankton photoacclimation, i.e., the increased absorption of CDOM leads to decreased light availability and in turn the phytoplankton produce more chlorophyll in response. For example, as supporting evidence, the IOP-based algorithm here has an exponential form that is similar to the photoacclimation form,[16] i.e., it has been shown[16] that, for 342 observations related to 23 phytoplankton species,

$$\langle Chl_{norm} \rangle = 0.036 + 0.3 \exp(-1.1\, I_g).$$

Here $\langle Chl_{norm} \rangle$ is a normalized cellular chlorophyll biomass and I_g is the growth irradiance (in mol quanta m^{-2} h^{-1}), i.e., the cellular chlorophyll declines exponentially with increasing growth irradiance. Note that a specific growth irradiance wavelength is unspecified in the theory given in Ref. 16. For satellite remote sensing purposes, one can attempt to capture the above laboratory-derived exponential variation by assuming that the *in situ* oceanic photoacclimation-induced chlorophyll biomass $\langle Chl \rangle_{oceanic\ photoacc}$ is given by

$$\langle Chl \rangle_{oceanic\ photoacc} \sim \exp[-sE_d(Z)], \qquad (13)$$

where $E_d(Z)$ (in W m^{-2} nm^{-1}) is the plane irradiance at depth Z and serves as a reasonable surrogate for the laboratory growth irradiance. Here s is defined as the slope of irradiance versus chlorophyll photoacclimation within an oceanic province. Prior research[16] strongly suggests that s is species dependent, but for satellite remote sensing purposes s must initially be considered to be a single global species average. But at any depth, $E_d(Z) = E_d(0^-)\exp(-K_d Z)$ where $E_d(0^-)$ is the downwelling irradiance just beneath the ocean surface. The IOPs enter by $K_d \approx (a + b_b)/\mu$ where $a = a_w + a_{ph} + a_{CDOM}$, b_b is the total backscattering, and μ is the average cosine of the downwelling light field. As with Eq. (11), the photoacclimation hypothesis given by Eq. (13) also suggests that IOPs play a strong role in the chlorophyll variability in the global oceans. Additional modeling and analysis studies, outside the scope of this paper, are required to demonstrate equivalence, if any, of the IOP-based chlorophyll retrieved by Eq. (11) and the photoacclimation-induced chlorophyll biomass variability as given by Eq. (13).